

# CPT AND LORENTZ TESTS WITH CLOCKS IN SPACE

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Space-based clock-comparison experiments can provide Planck-scale sensitivity to many parameters for Lorentz and CPT violation that are difficult to measure on Earth. The principal advantages are a reduced timescale for data collection, reduced suppression for certain effects, and access to certain parameters not possible with Earth-based experiments.

## 1 Introduction

The standard model of particle physics is covariant under rotations and boosts, which together make up the Lorentz transformations. Violation of Lorentz symmetry<sup>1</sup> might occur in the context of string theory, accompanied possibly by violation of CPT symmetry.<sup>2</sup> Observation of such violations would provide information about noncommutative field theories,<sup>3</sup> and would represent evidence of Planck-scale physics. It is unlikely that they could be directly observed, but suppressed effects might be reachable with high-sensitivity experiments. The description of observable effects is given by a standard-model extension that allows for violation of both Lorentz and CPT symmetry.<sup>4</sup>

Clock-comparison experiments with atoms and ions<sup>5,6,7,8</sup> are some of the most sensitive existing tests of Lorentz and CPT symmetry in matter. These search for violations of rotational symmetry by monitoring the frequency variations of a Zeeman hyperfine transition as the quantization axis changes direction. The usual configuration involves comparing the frequencies of two different co-located clocks as the laboratory rotates with the Earth. Sensitivity to suppressed effects from the Planck scale can be achieved with experiments of this type.<sup>9</sup> Other sectors of the standard-model extension can be accessed through different experiments involving hadrons,<sup>10,11,12,13,14</sup> photons,<sup>4,15</sup> muons,<sup>16</sup> and electrons.<sup>17,18</sup>

This article aims to show that tests of Lorentz and CPT symmetry with Planck-scale sensitivity can be fruitfully pursued with clock-comparison experiments on satellites and other spacecraft.<sup>19</sup> We consider generalities of space experiments and discuss feasible tests for some specific orbital and deep-space missions, including a few approved for the International Space Station (ISS).

Certain Zeeman hyperfine transitions are shifted in frequency by the presence of Lorentz and CPT violation.<sup>9</sup> For a clock operating on such a transition, contributions to these shifts are controlled at leading order by a few parameters denoted in the clock reference frame as  $\tilde{b}_3^w$ ,  $\tilde{c}_q^w$ ,  $\tilde{d}_3^w$ ,  $\tilde{g}_d^w$ ,  $\tilde{g}_q^w$ . Here, the superscript  $w$  is  $p$  for the proton,  $n$  for the neutron, and  $e$  for the electron. These quantities are particular combinations of the basic coefficients  $a_\mu^w$ ,  $b_\mu^w$ ,  $c_{\mu\nu}^w$ ,  $d_{\mu\nu}^w$ ,  $e_\mu^w$ ,  $f_\mu^w$ ,  $g_{\lambda\mu\nu}^w$ ,  $H_{\mu\nu}^w$  appearing in the standard-model extension. They are related to expectation values in the underlying fundamental theory. For example,

$$\tilde{b}_3^w = b_3^w - m_w d_{30}^w + m_w g_{120}^w - H_{12}^w, \quad (1)$$

where  $m_w$  is the mass of the particle of type  $w$  and the subscripts are indices defined in a reference frame with the 3 direction defined as the clock quantization axis.

## 2 Reference Frames

We first consider a clock in a laboratory on the surface of the Earth. Then the sidereal rotation of the Earth, with period 23 h 56 min  $\simeq 2\pi/\Omega$ , gives rise to related variations in the parameters  $\tilde{b}_3^w$ ,  $\tilde{c}_q^w$ ,  $\tilde{d}_3^w$ ,  $\tilde{g}_d^w$ ,  $\tilde{g}_q^w$ . This time dependence can be found by considering the transformation from the clock frame with coordinates  $(0, 1, 2, 3)$  to a nonrotating frame with coordinates  $(T, X, Y, Z)$ . Ideally, the nonrotating frame should be inertial, but for practical purposes any frame close enough to inertial to achieve the desired experimental sensitivity would suffice. Frames associated with the Earth, the Sun, the Milky Way galaxy, or the cosmic microwave background radiation are examples of possible choices for the nonrotating frame. In previous literature, the nonrelativistic conversion from the clock frame to the nonrotating frame has been considered. However, the high velocities attainable in space-based experiments make it attractive to consider also leading-order relativistic effects due to clock boosts. Existing experimental bounds are unaffected by this choice of nonrotating frame since they ignored the translational motion of the clock. However, an Earth-centered choice is not appropriate for relativistic experiments because it is inertial over a limited time scale of perhaps a few days. Alternatively, frames centered on the Sun, the galaxy, or the microwave background are approximately inertial over thousands of years. This choice of frame must be stated when reporting bounds, but all of these are acceptable.

We adopt the Sun-based frame as a natural choice for experiments. It is convenient to center the spatial origin on the Sun with the unit vector  $\hat{Z}$  parallel to the Earth's rotation axis,  $\hat{X}$ ,  $\hat{Y}$  in the equatorial plane, and  $\hat{X}$  directed towards the celestial vernal equinox. Time  $T$  is measured from the

vernal equinox in the year 2000 using a clock located at the spatial origin. In this inertial frame, the Earth orbits about the Sun in a plane lying at an angle of  $\eta \simeq 23^\circ$  with respect to the  $XY$  plane.

It will suffice to approximate the Earth's orbit as circular with angular frequency  $\Omega_\oplus$  and speed  $\beta_\oplus$ . In the same way, a satellite orbit about the Earth can be approximated as circular with angular frequency  $\omega_s$  and speed  $\beta_s$ . The angle between  $\hat{Z}$  and the axis of the satellite orbit will be denoted by  $\zeta$ , and the right ascension angle of the ascending node of the orbit will be denoted by  $\alpha$ . The oblateness of the Earth and other perturbations cause  $\alpha$  to precess by about 4 degrees per day.

Expressed in the Sun-based frame, the clock boost is  $\vec{V}(T) = d\vec{X}/dT$ , where the instantaneous spatial location  $\vec{X}(T)$  of the clock is determined by the trajectories of the spacecraft and the Earth. This vector  $\vec{V}(T)$  determines the dilation of infinitesimal time intervals in the clock frame relative to ones in the Sun-based frame. Effects such as small perturbations in  $\vec{V}(T)$  and the gravitational potential should be included in an accurate relation between the two times. However, these corrections are irrelevant when two clocks at essentially the same location are compared. According to conventional relativity, the clocks then keep identical time independent of their composition. However, in the presence of Lorentz and CPT violation a signal that cannot be mimicked in conventional relativity is generated, because two co-located clocks involving different atomic species typically behave differently.

Depending on the flight mode of the satellite, the orientation of the clock quantization axis may change relative to the Sun frame. For this article, we focus on a flight mode and clock configuration where the clock quantization axis is tangential to the circular satellite trajectory about the Earth. So, the reference frame for the clock is chosen with 1 axis pointing towards the center of the Earth, 2 axis perpendicular to the satellite orbital plane, and 3 axis parallel to the satellite motion about the Earth. This configuration should be possible with planned modes for the ISS. Other spacecraft flight modes and quantization-axis orientations can be handled by our general methodology. It should be noted that to gain optimal sensitivity to certain components specific quantization-axis orientations relative to the plane of the orbit and the angular momentum vector would be required.

By combining the boost  $\vec{V}(T)$  of the orbiting clock with its rotation, the signal in the clock frame can be converted to the Sun-based frame. The idea is that components of the coefficients for Lorentz violation in the clock frame are to be expressed in terms of components in the Sun-based frame. For example,

the component  $b_3^w$  becomes

$$\begin{aligned}
b_3^w = & b_T^w \{ \beta_s - \beta_\oplus [\sin \Omega_\oplus T (\cos \alpha \sin \omega_s \Delta T \\
& + \cos \zeta \sin \alpha \cos \omega_s \Delta T) - \cos \eta \cos \Omega_\oplus T \\
& \times (\sin \alpha \sin \omega_s \Delta T - \cos \zeta \cos \alpha \cos \omega_s \Delta T) \\
& + \sin \eta \cos \Omega_\oplus T \sin \zeta \cos \omega_s \Delta T] \} \\
& - b_X^w (\cos \alpha \sin \omega_s \Delta T + \cos \zeta \sin \alpha \cos \omega_s \Delta T) \\
& - b_Y^w (\sin \alpha \sin \omega_s \Delta T - \cos \zeta \cos \alpha \cos \omega_s \Delta T) \\
& + b_Z^w \sin \zeta \cos \omega_s \Delta T,
\end{aligned} \tag{2}$$

where  $\Delta T = T - T_0$  is the time interval measured from an agreed reference time  $T_0$ . Effects such as the Thomas precession are neglected, since the equation holds to leading order in linear velocities. The full result for the Sun-frame observable parameter  $\tilde{b}_3^w$  involves the expression (2) for the component  $b_3^w$  as well as expressions for other coefficients. The other observables  $\tilde{c}_q^w$ ,  $\tilde{d}_3^w$ ,  $\tilde{g}_d^w$ , and  $\tilde{g}_q^w$  are found by a similar procedure. The expressions are lengthy, depending on various combinations of basic coefficients for Lorentz and CPT violation, on trigonometric functions of various angles, on frequency-time products, on  $\beta_\oplus$ , and on  $\beta_s$ .

### 3 Signal Properties

All the spatial components of the basic coefficients for Lorentz and CPT violation are directly accessible with space-based experiments. Ground-based clock-comparison experiments seeking frequency variations as the Earth rotates are limited by the fixed rotation axis, which means sensitivity to certain spatial components is not possible. For instance, ground-based experiments are sensitive only to the nonrotating-frame components  $\tilde{b}_X^w$ ,  $\tilde{b}_Y^w$  of the parameter  $\tilde{b}_3^w$ , and can therefore only bound a limited subset of components of  $b_\mu^w$ ,  $d_{\mu\nu}^w$ ,  $g_{\lambda\mu\nu}^w$ ,  $H_{\mu\nu}^w$ . All spatial components can however be accessed with an orbiting satellite. Typically, satellites offer different sensitivity from Earth-based experiments since their orbital plane is tilted with respect to the equatorial plane. Furthermore, the precession of the satellite orbital plane makes it possible in principle to access all spatial directions.

Another advantage of space-based experiments is the relatively short orbital period, a result of their high orbital speeds. Since the satellite orbital period  $2\pi/\omega_s$  is typically much less than the sidereal day, the time required to collect data can be substantially reduced. For example, a clock-comparison experiment on the ISS could be completed approximately 16 times faster than

an Earth-based one, since the ISS orbital period is about 92 min. This better matches clock stabilities and reduces the run time from months to days. This makes possible an analysis of the leading-order relativistic effects due to the speed  $\beta_{\oplus} \simeq 1 \times 10^{-4}$  of the Earth in the Sun-based frame. As a result, sensitivity to many more types of Lorentz and CPT violation can be achieved. Existing ground-based clock-comparison experiments might take data over months, during which the Earth's velocity vector changes direction significantly. In space-based experiments, this vector could be treated as approximately constant if the timescale for data collection is short enough. This would considerably simplify the experimental analysis since the Earth could be regarded as an inertial frame, thus permitting direct extraction of leading-order relativistic effects.

Sensitivity to many types of Lorentz and CPT violation that remain unconstrained to date could be achieved with space-based experiments. For example, consider a clock-comparison experiment sensitive to the observable  $\tilde{b}_3^w$  for some  $w$ . In the Sun-based frame and for each particle species  $w$ , this observable involves the basic coefficients  $b_\mu^w$ ,  $d_{\mu\nu}^w$ ,  $g_{\lambda\mu\nu}^w$ ,  $H_{\mu\nu}^w$  for Lorentz violation, a total of 35 independent observable components if allowance is made for the effect of field redefinitions. Whereas a traditional ground-based experiment is sensitive to 8 of these, the same type of experiment mounted on a space platform would acquire sensitivity to all 35. We note that experiments could be envisaged using an Earth-based rotating turntable to gain access to a wider set of parameters. The emphasis here is on understanding and optimizing sensitivities envisaged for planned space missions.

For Earth-based experiments, relativistic Lorentz and CPT terms are suppressed by the boost factor  $\beta_{\oplus}$ . However, space-based clock-comparison experiments would be sensitive to first-order relativistic effects proportional to  $\beta_s$ . Investigating the corresponding effects in Earth-based experiments would be impractical, and in any case these would be further suppressed by a factor of  $\Omega/\omega_s$ . For the ISS,  $\Omega/\omega_s$  is about  $6 \times 10^{-2}$ .

A seemingly counterintuitive effect exists among the order- $\beta_s$  corrections. In space-based experiments a dipole shift can generate a potentially detectable signal with frequency  $2\omega_s$ . This is not seen in the usual nonrelativistic analysis of ground-based clock-comparison experiments, where signals with the double frequency  $2\Omega$  occur only in quadrupole shifts. To gain insight into this, consider the parameter  $\tilde{b}_3^w$ , which nonrelativistically is the third component of a vector and so would lead only to a signal with frequency  $\omega_s$ . However,  $\tilde{b}_3^w$  contains the component  $d_{03}$ . In a relativistic treatment incorporating first-order effects from  $\beta_s$  it behaves like a two-tensor and hence can produce a signal with frequency  $2\omega_s$ . As an example, when the Earth is near the northern-summer solstice, the expression for  $\tilde{b}_3^w$  in the Sun-based frame has a double frequency

term that goes like  $\cos(2\omega_s \Delta T)$  with coefficient  $C_2$  containing the following spatial components of  $d_{\mu\nu}^w$ :

$$\begin{aligned}
C_2 \supset \beta_s \frac{m}{8} & [\cos 2\alpha (3 + \cos 2\zeta) (d_{XX}^w - d_{YY}^w) \\
& + (1 - \cos 2\zeta) (d_{XX}^w + d_{YY}^w - 2d_{ZZ}^w) \\
& - 2\sin 2\zeta (\cos \alpha (d_{YZ}^w + d_{ZY}^w) - \sin \alpha (d_{ZX}^w + d_{XZ}^w)) \\
& + (3 + \cos 2\zeta) \sin 2\alpha (d_{XY}^w + d_{YX}^w)]. \tag{3}
\end{aligned}$$

Sensitivity to all observable spatial components of  $d_{\mu\nu}^w$  could thus be achieved by observing the  $2\omega_s$  frequency.

## 4 Earth-Satellite Experiments

The ISS is of special interest since it is the planned platform for numerous scientific experiments in the near future. For the ISS, the relevant orbital parameters include  $\beta_s \simeq 3 \times 10^{-5}$  and  $\zeta \simeq 52^\circ$ . Instruments planned for installation are H masers, laser-cooled Cs and Rb clocks, and superconducting microwave cavity oscillators.<sup>20,21,22,23</sup> Advantages for experiments on the ISS include a microgravity environment and reduced environmental disturbances, which are expected to lead to gains in sensitivity compared to existing ground-based clocks. The analysis presented here is valid for possible Lorentz and CPT tests with all these instruments, except the oscillators.<sup>24</sup> For the present discussion, we assume the signal clock is compared to a co-located reference clock insensitive to leading-order Lorentz and CPT violation. This could be an H maser tuned to its clock transition  $|1, 0\rangle \rightarrow |0, 0\rangle$ , for example.

### 4.1 Hydrogen masers

One option would be to use an H maser as the signal clock as well as the reference clock. Such an experiment would be similar to a recent ground-based Lorentz and CPT test, which measured the maser transition  $|1, \pm 1\rangle \rightarrow |1, 0\rangle$  using a double-resonance technique.<sup>8</sup> Sensitivity would be to the parameters  $\tilde{b}_3^p$  and  $\tilde{b}_3^e$  in the clock frame and the analysis in this case has the advantage that the atoms used are relatively simple compared with those in other atomic-clock experiments. In addition, the short ISS orbital period implies that an experimental run of about a day would be sufficient to obtain data roughly equivalent to four months of data taken on Earth. For both  $w = e$  and  $w = p$ , all spatial components of  $b_\mu^w$ ,  $m_w d_{\mu\nu}^w$ ,  $m_w g_{\lambda\mu\nu}^w$ ,  $H_{\mu\nu}^w$  could be sampled by using the orbital inclination ( $\zeta \neq 0$ ) and by repeating the experiment with a different value of  $\alpha$ . We estimate that several presently unbounded components would

be tested at the level of about  $10^{-27}$  GeV, while others would be tested at about  $10^{-23}$  GeV. This is based on the assumption that previous sensitivities of about 500  $\mu\text{Hz}$  can be achieved in space. Cleaner bounds on certain components of  $m_w d_{\mu\nu}^w, m_w g_{\lambda\mu\nu}^w$  at the level of about  $10^{-23}$  GeV could be obtained by searching for a signal at the double frequency  $2\omega_s$ . Planck-scale sensitivity to about 50 components of coefficients for Lorentz and CPT violation that are currently unconstrained could be tested in this way.

#### 4.2 Cesium Clocks

The reference frequency for a laser-cooled  $^{133}\text{Cs}$  clock could be the usual clock transition  $|4, 0\rangle \rightarrow |3, 0\rangle$ , which is insensitive to Lorentz and CPT violation. An attractive signal transition in the present context would be a Zeeman hyperfine transition such as  $|4, 4\rangle \rightarrow |4, 3\rangle$ . Since the electronic configuration of  $^{133}\text{Cs}$  involves an unpaired electron, the electron-parameter sensitivity is similar to that of the H maser. In the Schmidt model, the  $^{133}\text{Cs}$  nucleus is a proton with angular momentum  $7/2$ , providing sensitivity to all clock-frame parameters  $\tilde{b}_3^p, \tilde{c}_q^p, \tilde{d}_3^p, \tilde{g}_d^p, \tilde{g}_q^p$ , and so yielding both dipole and quadrupole shifts. Among the components tested would be  $c_{\mu\nu}^p$ . As a guide to what might be achieved, we note that an Earth-based experiment based on the  $|4, 4\rangle \rightarrow |4, 3\rangle$  transition achieved the sensitivity level of about 50  $\mu\text{Hz}$ .<sup>6</sup> A similar experiment on the ISS would be reduced in duration by a factor of 16. Furthermore, an investigation of the double-frequency signal  $2\omega_s$  would give access to the spatial components of  $c_{\mu\nu}^p$  at the  $10^{-25}$  level, and to other components at about the  $10^{-21}$  level. In all, about 60 components of coefficients for Lorentz and CPT violation would be accessible with Planck-scale sensitivity.

#### 4.3 Rubidium Clocks

Experiments with  $^{87}\text{Rb}$  have similar features to experiments with  $^{133}\text{Cs}$ . A suitable reference signal would be the standard  $|2, 0\rangle \rightarrow |1, 0\rangle$  clock transition, which is insensitive to Lorentz and CPT violation, while a Zeeman hyperfine transition such as  $|2, 1\rangle \rightarrow |2, 0\rangle$  could be used as a signal clock. Due to its unpaired electron,  $^{87}\text{Rb}$  has sensitivity to electron parameters similar to that of an H maser or a Zeeman hyperfine transition in  $^{133}\text{Cs}$ . The sensitivity to proton parameters is also analogous to that of  $^{133}\text{Cs}$  up to factors of order unity, because the Schmidt nucleon for  $^{87}\text{Rb}$  is a proton with angular momentum  $3/2$ . The fact that the nuclear configuration has magic neutron number means theoretical calculations may be more reliable and that experimental results would be cleaner.<sup>9</sup> As with the case of  $^{133}\text{Cs}$ , numerous Lorentz and CPT tests sensitive to Planck-scale effects could be done.

#### 4.4 Other Spacecraft

Important Lorentz and CPT tests could also be done with other types of spacecraft. Of special interest would be missions where the speeds of the craft with respect to the Sun are larger than the  $\beta_s$  possible with satellites orbiting the Earth. One example is the planned SpaceTime<sup>25</sup> experiment, which will attain  $\beta \simeq 10^{-3}$  on a solar-infall trajectory from Jupiter. This mission will fly co-located  $^{111}\text{Cd}^+$ ,  $^{199}\text{Hg}^+$ , and  $^{171}\text{Yb}^+$  ion clocks in a craft rotating several times per minute, so that even 15 min might be long enough to gather useful data for Lorentz and CPT tests. For each of the three clocks, the clock transitions  $|1, 0\rangle \rightarrow |0, 0\rangle$  are unaffected by Lorentz and CPT violation and so could be used as reference signals. A signal clock would run on a Zeeman hyperfine transition such as  $|1, 1\rangle \rightarrow |1, 0\rangle$ . Sensitivity to electron parameters would then be possible due to the electron configuration. All three clocks would have sensitivity to the neutron parameters  $\tilde{b}_3^n$ ,  $\tilde{d}_3^n$ ,  $\tilde{g}_d^n$  in the clock frame, because the Schmidt nucleon for all three isotopes is a neutron with angular momentum 1/2. Such experiments are important because none of the above neutron parameters can be probed with the proposed ISS experiments. By searching for variations in the signal clocks at the spacecraft rotation frequency  $\omega_{ST}$  and also at  $2\omega_{ST}$  numerous tests for Lorentz and CPT violation would be possible. Experiments of this type would have an order of magnitude greater sensitivity to Lorentz and CPT violation than measurements performed either on the Earth or in orbiting satellites because of their large boost.

## 5 Discussion

There are numerous interesting prospects for investigating CPT and Lorentz symmetry violation using space-based experiments. These include experiments planned for the International Space Station in the coming decade. These experiments will be able to exploit the relatively high rotation rates of the ISS as well as the relatively high speed of motion around the Earth to gain sensitivity to relativistic effects within the context of the standard-model extension.

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